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## POLARIZED NARROW-LINE EMISSION FROM THE NUCLEUS OF NGC 4258

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## ABSTRACT

The detection of polarized continuum and line emission from the nucleus of NGC 4258 by Wilkes et al. (1995) provides an intriguing application of the unified model of Seyfert nuclei to a galaxy in which there is known to be an edge-on, rotating disk of molecular gas surrounding the nucleus. Unlike most Seyfert nuclei, however, NGC 4258 has strongly polarized *narrow* emission lines. To further investigate the origin of the polarized emission, we have obtained spectropolarimetric observations of the NGC 4258 nucleus at the Keck-II telescope. The narrow-line polarizations range from 1.0% for [S II]  $\lambda$ 6716 to 13.9% for the [O II]  $\lambda\lambda$ 7319,7331 blend, and the position angle of polarization is oriented nearly parallel to the projected plane of the masing disk. A correlation between critical density and degree of polarization is detected for the forbidden lines, indicating that the polarized emission arises from relatively dense ( $n_e \gtrsim 10^4 \text{ cm}^{-3}$ ) gas. An archival *Hubble Space Telescope* narrow-band [O III] image shows that the narrow-line region has a compact, nearly unresolved core, implying a FWHM size of  $\lesssim 2.5$  pc. We discuss the possibility that the polarized emission might arise from the accretion disk itself and become polarized by scattering within the disk atmosphere. A more likely scenario is an obscuring torus or strongly warped disk surrounding the inner portion of a narrow-line region which is strongly stratified in density. The compact size of the narrow-line region implies that the obscuring structure must be smaller than  $\sim 2.5$  pc in diameter.

*Subject headings:* galaxies: active – galaxies: individual (NGC 4258) — galaxies: nuclei – galaxies: Seyfert — polarization

## 1. INTRODUCTION

The low-luminosity Seyfert galaxy NGC 4258 provides some of the most convincing evidence for a link between supermassive black holes and nuclear activity. Its nucleus exhibits hard X-ray emission (Makishima et al. 1994), broad H $\alpha$  emission (Filippenko & Sargent 1985; Ho et al. 1997a), and jets which have been observed on subparsec scales in radio continuum emission (Herrnstein et al. 1997a). The kiloparsec-scale “anomalous arms” observed in optical emission lines, X-rays, and radio emission (Courtès & Cruvelliér 1961; Cecil et al. 1995 and references therein) are thought to be the outer extensions of the nuclear jet (but see Cox & Downes 1996 for an alternative interpretation). Based on these observations, it is clear that NGC 4258 contains a genuine low-luminosity active nucleus. The discovery of a rotating molecular disk emitting H<sub>2</sub>O maser lines provides a unique means to trace out the nuclear rotation curve in the inner parsec. Miyoshi et al. (1995) have shown that the disk rotation is Keplerian and implies a central mass of  $3.6 \times 10^7 M_\odot$  within a radius of 0.13 pc (for a distance of 6.4 Mpc). Alternatives to a supermassive black hole are implausible, because the derived central mass density is so large that a hypothetical cluster of dark objects would have a lifetime of at most  $\sim 5 \times 10^8$  yr against evapo-

ration and/or collisions (Maoz 1998). This combination of nuclear activity, a well-determined central mass, and a rotating circumnuclear disk makes NGC 4258 a particularly interesting laboratory in which to study many aspects of the AGN phenomenon.

NGC 4258 is a natural target for spectropolarimetric investigation, because the nuclear disk is nearly edge-on. Wilkes et al. (1995; hereafter W95) discovered that the emission lines and continuum in NGC 4258 are polarized, with the angle of polarization nearly parallel to the disk plane (P.A. =  $86^\circ$ ; Miyoshi et al. 1995). This coincident orientation was interpreted as evidence that the polarization is due to scattering by electrons or dust grains in clouds located above the plane of an optically thick torus. The discovery of polarized emission lines in NGC 4258 has important implications for unified model of AGNs, as it provides a direct link between polarized nuclear emission and the presence of an edge-on, parsec-scale molecular disk. It also suggests that the unified scheme can apply to even the lowest luminosity Seyfert nuclei. One interesting aspect of the W95 results is the unusually high polarization of the narrow emission lines (4.6% for [O I]  $\lambda$ 6300). In typical Seyfert 2 nuclei the narrow lines are unpolarized, or are weakly polarized by transmission through dust in the

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host galaxy (Goodrich 1992). In this paper, we focus on the polarization mechanism of the narrow emission lines, using Keck spectropolarimetry data and archival *Hubble Space Telescope* (*HST*) images. In the following discussion, we assume a distance of 7.3 Mpc to NGC 4258, based on recent observations of proper motions in the maser disk (Herrnstein et al. 1997b); at this distance,  $1''$  corresponds to 35 pc, and the central mass measured by Miyoshi et al. (1995) scales to  $4.1 \times 10^7 M_{\odot}$ .

## 2. OBSERVATIONS AND RESULTS

### 2.1. Spectropolarimetry

The observations were obtained on 1997 April 10 UT at the Keck-II telescope using the LRIS spectropolarimeter (Oke et al. 1995; Cohen et al. 1997). The seeing was  $0''.6$ – $0''.7$ , and conditions were photometric. We used a  $300 \text{ grooves mm}^{-1}$  grating blazed at  $5000 \text{ \AA}$  and a  $1''$  slit, yielding a spectral range of  $3800$ – $8700 \text{ \AA}$ , and the spatial scale was  $0''.215 \text{ pixel}^{-1}$ . The spectral resolution, as measured from a comparison lamp exposure, varied from  $10 \text{ \AA}$  at the center of the spectrum to  $\sim 13 \text{ \AA}$  at the red and blue ends. The exposure time was 5 minutes for each of the four waveplate positions. The spectrograph slit was oriented east-west (P.A. =  $90^\circ$ ) during the observations, while the parallactic angle was  $50^\circ$ ; this offset affects the shape of the polarized continuum at the blue end of the spectrum, as we discuss below. No order-blocking filter was used, and there may be some second-order light longward of  $7600 \text{ \AA}$ , but none of our conclusions are affected by this contamination.

The data were reduced with the VISTA software package (Terndrup et al. 1984) according to the methods described by Cohen et al. (1997) and Miller et al. (1988), using the polarized standard star HD 155528 (Clemens & Tapia 1990) to calibrate the position angle of polarization. Spectral extractions were performed using a width of  $3''.4$  along the slit, and the results are shown in Figure 1. A  $1''.1$ -wide extraction was also performed, in order to better isolate the nuclear emission, but the continuum polarization in the narrow extraction is more severely affected by the slit misalignment. The emission-line results for the two extractions are substantially similar, with most emission-line polarizations agreeing to within  $1\sigma$ , and all results in this paper refer to the  $3''.4$ -wide extraction.

To measure accurate line polarizations, starlight was subtracted from the total flux spectrum using the methods described by Ho et al. (1993) and Tran (1995), with a spectrum of the M31 nucleus used as a template. We were able to achieve a satisfactory continuum subtraction without including any nonstellar contribution, and we estimate that a nonstellar continuum source can contribute at most 5% of the flux in our aperture (provided that the stellar populations in the NGC 4258 and M31 nuclei have similar metallicities). All polarization measurements were carried out on the Stokes parameter ( $q$  and  $u$ ) spectra, with the results converted to degree and position angle of polarization ( $p$  and  $\theta$ ) only as the final step. The polarizations of unblended lines were measured by direct integration of the fluxes and Stokes parameters using the methods out-

lined by Miller et al. (1988). Table 1 lists the individual emission-line polarizations.

The polarizations of the individual components of the  $\text{H}\alpha$ + $[\text{N II}]$  and  $[\text{S II}]$  blends were measured by fitting the emission profiles in the total flux ( $f$ ) spectrum and in the  $f \times q$  and  $f \times u$  spectra, using the SPECFIT package within IRAF. Our observations do not have sufficient spectral resolution to determine whether there is a broad component of  $\text{H}\alpha$  in total flux; a good fit to the  $\text{H}\alpha$ + $[\text{N II}]$  profile can be achieved either with or without the inclusion of a broad  $\text{H}\alpha$  component. The higher resolution observations of Ho et al. (1997a) demonstrate that the total flux spectrum contains a broad  $\text{H}\alpha$  component of  $\text{FWHM} \approx 1700 \text{ km s}^{-1}$  which is not present in the profiles of the narrow forbidden lines, but the Ho et al. observations were obtained in 1984 and the broad-line flux could be variable<sup>8</sup>. Therefore, we measured the  $\text{H}\alpha$  and  $[\text{N II}]$  component polarizations by fitting multi-Gaussian models both with and without a broad  $\text{H}\alpha$  component. Since our data do not clearly demonstrate the existence of the broad  $\text{H}\alpha$  component, we take as our “default” results the line polarizations measured by fitting the blend without a broad  $\text{H}\alpha$  component; these results are listed in Table 1.

In the fits which do include a broad  $\text{H}\alpha$  component, the width of broad  $\text{H}\alpha$  is not well constrained, so the broad component was fixed to have  $\text{FWHM} = 1700 \text{ km s}^{-1}$  to match the results of Ho et al. (1997a). For these fits, the resulting polarizations are  $p = 12.2\% \pm 1.1\%$  for broad  $\text{H}\alpha$ ,  $p = 2.7\% \pm 0.6\%$  for narrow  $\text{H}\alpha$ , and  $p = 3.4\% \pm 0.6\%$  for  $[\text{N II}] \lambda 6584$ . The quoted uncertainties represent the formal errors of the fits, while the actual uncertainties must be significantly larger because the data do not show whether the broad  $\text{H}\alpha$  component is in fact present.

The Keck data confirm the general results found by W95: the narrow emission lines are polarized with position angles (PAs) of typically  $89 - 90^\circ$ , close to the projected  $86^\circ$  PA of the masing disk. We find somewhat higher line polarizations than those measured by W95, who used a  $3'' \times 7''$  effective aperture, most likely because our smaller  $1'' \times 3''.4$  aperture admits less unpolarized emission-line light from the outer regions of the narrow-line region (NLR). Similarly, the continuum polarization of 0.35% in the  $V$ -band region is greater than that measured by W95, who found  $p = 0.23\%$  over  $5100$ – $6500 \text{ \AA}$ . Most of this continuum polarization must be intrinsic to NGC 4258 rather than due to transmission through Galactic dust, since a Galactic reddening of  $E(B - V) = 0.016$  mag (Schlegel et al. 1998) should result in a polarization of at most 0.14% (Serkowski et al. 1975). Furthermore, the similar position angles of the line and continuum polarization suggest that the continuum polarization is not dominated by interstellar dust transmission.

The linewidths listed in Table 1 were measured by fitting Gaussian profiles to each emission feature, and subtracting the instrumental resolution in quadrature from the measured widths. Figure 2 compares the emission-line profiles in total flux and Stokes flux. As found by W95, the emission lines are broader in polarized light than in the total flux spectrum. This is most clearly visible for  $[\text{O III}] \lambda 5007$ , which has  $\text{FWHM} = 530 \text{ km s}^{-1}$  in total

<sup>8</sup>We note that W95 do not discuss whether a broad component of  $\text{H}\alpha$  may be present in polarized flux. Their  $400 \text{ km s}^{-1}$  spectral resolution is somewhat higher than that of our observations but still not sufficient to permit the unambiguous detection of a  $1700 \text{ km s}^{-1}$  broad component of  $\text{H}\alpha$  by fitting the  $\text{H}\alpha$ + $[\text{N II}]$  blend.

flux and  $1010 \text{ km s}^{-1}$  in Stokes flux. The  $\text{H}\alpha + [\text{N II}]$  blend has nearly the same FWHM in total and Stokes flux, but a broader base appears in Stokes flux, particularly on the red side of the profile, and the narrow  $\text{H}\alpha$  peak is broader in Stokes flux.

Figure 2 also shows that the  $[\text{O III}] \lambda 5007$  line is blueshifted in Stokes flux relative to its profile in total light. In the observed wavelength frame, the  $\lambda 5007$  line has centroid  $5011.0 \pm 0.6 \text{ \AA}$  in total flux and  $5008.9 \pm 0.4 \text{ \AA}$  in Stokes flux, for a shift of  $126 \text{ km s}^{-1}$  with a significance level of  $2.9\sigma$ . The other lines are too noisy in Stokes flux to determine whether there is a significant velocity shift relative to the profiles in total flux.

One remarkable feature of the Stokes flux spectrum is the weakness of polarized  $[\text{S II}]$  emission relative to the other emission features (as noted by W95), and the fact that the  $[\text{S II}] \lambda 6716/6731$  flux ratio appears to be greater in total light than in Stokes flux. Such a change in the relative strengths of two closely spaced lines cannot be a result of the interaction with the scattering medium; the more likely cause is that the scattering medium “sees” a different  $[\text{S II}]$  ratio, and therefore a different density, than what is observed in the total flux spectrum. In total flux,  $I(\lambda 6716)/I(\lambda 6731) = 0.94$ , corresponding to a density of  $n_e = 750 \text{ cm}^{-3}$  at  $T_e = 10^4 \text{ K}$ . The  $[\text{S II}]$  ratio in polarized light is  $0.31 \pm 0.20$ , formally lower than (but consistent with) the theoretical minimum value of 0.44 for the high-density limit, and yielding a density of  $n_e \gtrsim 10^4 \text{ cm}^{-3}$  (Czyzak et al. 1986).

The other forbidden lines exhibit similar behavior. Figure 3 shows the degree of polarization of the forbidden lines as a function of the critical density for collisional de-excitation ( $n_{crit}$ ) of each line, and also as a function of the ionization potential (IP) of the ionization state giving rise to each line. A trend is apparent: although there is considerable scatter, lines of greater  $n_{crit}$  tend to be more highly polarized than lines of lower  $n_{crit}$ , and the trend appears to apply at least in a rough sense over nearly four orders of magnitude in  $n_{crit}$ . The significance of the correlation between  $p$  and  $n_{crit}$  depends on which value for  $p([\text{N II}] \lambda 6584)$  is used: the value of 7.7% derived from the 3-Gaussian fit to the  $\text{H}\alpha + [\text{N II}]$  blend, or the lower value of 3.4% derived from the 4-Gaussian fit with a broad  $\text{H}\alpha$  component.

For the  $p$ - $n_{crit}$  relation using the value of  $p([\text{N II}])$  derived from the fit without a broad  $\text{H}\alpha$  component, we find a Spearman rank correlation coefficient of  $r_s = 0.68$ , which would arise by chance between unrelated variables only 9.4% of the time (a two-tailed probability). The correlation coefficient is similarly high if lines with nearly equal values of  $p$  are given identical rank. A marginally significant correlation is apparent between polarization and IP ( $r_s = 0.59$ , 16% probability of arising by chance). Using the lower value of  $p([\text{N II}]) = 3.4\%$  from the 4-Gaussian fit, however, the correlation between  $p$  and  $n_{crit}$  improves to  $r = 0.89$ , with only an 0.7% probability of arising by chance. Since the higher-resolution spectra of Ho et al. (1997a) indicate that a significant broad-line component of  $\text{H}\alpha$  was present in 1984, the lower value of  $p([\text{N II}]) = 3.4\%$  from the 4-Gaussian fit may be preferable to the “default” higher value of  $p = 7.7\%$  obtained from the 3-Gaussian fit.

Similar correlations, but between linewidth and  $n_{crit}$ , have been discovered in Seyferts and LINERs (e.g., Pelat et al. 1981; Filippenko & Halpern 1984; Filippenko 1985), although NGC 4258 is the first Seyfert known to show a relationship between  $p$  and  $n_{crit}$ . The Keck data do not have sufficient spectral resolution to properly evaluate a possible correlation between linewidth and  $n_{crit}$ , but such a correlation may be present, as the high- $n_{crit}$  lines of  $[\text{O I}]$  and  $[\text{O III}]$  are broader than the low- $n_{crit}$  lines of  $[\text{N II}]$  and  $[\text{S II}]$ . The large FWHM of  $870 \text{ km s}^{-1}$  for  $[\text{O II}] \lambda 7325$  is partly due to the fact that it is a blend of components with rest wavelengths at 7319 and 7331  $\text{\AA}$ , with possible  $[\text{Ca II}]$  emission at 7324  $\text{\AA}$  as well.

## 2.2. Archival HST Images

To search for morphological evidence for an obscuring torus, we have examined an archival *HST* WFPC2/PC narrow-band image of the nucleus of NGC 4258 (Figure 4). The 2300 s exposure was taken on 1995 March 16 through the narrow-band F502N filter, which isolates the  $[\text{O III}] \lambda 5007$  line. Continuum emission was subtracted using an image of the same field taken in the F547M (V-band) filter. The F547M image was scaled so that the maximum amount of continuum emission was removed without leaving negative “holes” around the nucleus or at the positions of other stars in the field.

If the nuclear disk flares out to a thick obscuring torus extending out to radii of a few parsecs, such a structure might be apparent in the  $[\text{O III}]$  image as a dark band across the nucleus. Similarly, an ionization cone extending north-south would be another possible consequence of a thick torus. The *HST* image shows that the  $[\text{O III}]$ -emitting region is strongly peaked at the nucleus, with some extended emission surrounding the nuclear peak. The central spike of  $[\text{O III}]$  emission is only marginally more extended than a synthetic F502N point-spread function generated using the TinyTim package (Krist & Hook 1997), implying a FWHM size of  $\lesssim 2.5 \text{ pc}$ . The F547M continuum image, on the other hand, does not show evidence for a strong nuclear point source. This resolved continuum morphology is typical of Seyfert 2 nuclei (Nelson et al. 1996; Malkan et al. 1998).

Some interesting structure is seen in the extended  $[\text{O III}]$  emission on larger scales. The off-nuclear emission is concentrated in a faint region extending  $2''$  south of the nucleus and in a bright arc extending from  $\sim 2'' - 5''$  north of the nucleus, with prominent knots or filaments along the northwest portion of the arc. Since the extended emission is concentrated in patches located above and below the plane of the masing disk, these regions may represent ionization cones illuminated by anisotropic ionizing radiation from the AGN, or regions in which the nuclear jet interacts with interstellar clouds (Ford et al. 1996).

The *HST* images also allow us to make a quantitative assessment of whether the  $40^\circ$  offset between the slit angle and the parallactic angle may have had a negative impact on our data. At airmass 1.26, atmospheric dispersion will displace the emission from a point source by  $\sim 0''.25$  at 5000  $\text{\AA}$ , and by  $\sim 0''.61$  at 4000  $\text{\AA}$ , relative to the position of the source at 6500  $\text{\AA}$  (Filippenko 1982; recalculated for conditions appropriate to Mauna Kea). Since the LRIS guide camera views the red portion of the spectrum, the blue image of the nucleus would have appeared off-center

in the slit.

To assess the effects of this misalignment, we performed aperture photometry on the *HST* images using a  $1'' \times 3''.4$  rectangular aperture. The results that were obtained with the aperture centered on the nucleus were then compared with results obtained with the aperture centered off the nucleus at a position determined by the atmospheric dispersion. For the simulations, the “nuclear” region was defined as that portion of the image within a radius of  $r = 5$  PC pixels ( $0''.23$ ) surrounding the nucleus, which includes nearly all the light from the central [O III] emission spike. The images were convolved with a Gaussian of FWHM =  $0''.7$  prior to measurement, to match the seeing during the Keck run.

The simulations indicate that the observed fraction of [O III]  $\lambda 5007$  light coming from the nuclear region is 0.54, compared with a nuclear fraction of 0.56 that would have been obtained had the spectrograph slit been properly oriented at the parallactic angle. Assuming that the polarized emission originates from the central spike, this result implies that the measured polarization of [O III] is 0.96 times the polarization that would have been measured with the slit at the parallactic angle. Similarly, the measured nuclear fraction of the 5000 Å continuum is 0.95 times the value that would have been obtained at the parallactic angle. Thus, the region of the spectrum which includes most of the important emission lines is only slightly affected by the spectrograph slit misalignment. Blueward of 5000 Å, however, the measurements are more severely affected. At 4000 Å, the simulations indicate that the observed nuclear fraction is only 0.77 times the value that would have been measured with the slit at the parallactic angle. Thus, the  $p$  and Stokes flux spectra shown in Figure 1 should be revised upward by a factor of approximately 1.3 at the extreme blue end of the observed wavelength range, provided that the polarized emission source is as compact as we have assumed.

### 3. DISCUSSION

NGC 4258 appears analogous in some respects to higher-luminosity Seyfert 2 nuclei, but its narrow-line polarization properties are unlike those of most Seyfert 2 nuclei having hidden broad-line regions<sup>9</sup>. The X-ray continuum is heavily obscured ( $N_H \approx 1.5 \times 10^{23} \text{ cm}^{-2}$ ; Makishima et al. 1994), but it is not known whether this same obscuring material is distributed on large enough scales to cover a portion of the NLR as well. Since the narrow-line properties of NGC 4258 are so unusual, and there is no clear evidence for polarized broad emission lines, it is worthwhile to consider whether the obscuring torus model applies to this galaxy, or whether an entirely different mechanism could be responsible for the emission-line polarization.

Polarization by transmission through foreground dust is ruled out by the broadening of the line profiles seen in polarized light, and by the high line polarizations; a foreground polarization of 10% would require a high reddening of  $E(B - V) > 1$  mag. The narrow-line  $H\alpha/H\beta$  intensity ratio is 3.94 (Ho et al. 1997b), which corresponds to a reddening of  $E(B - V) = 0.24$  mag for an intrinsic  $H\alpha/H\beta$  ratio of 3.1, the value appropriate for gas pho-

toionized by an AGN continuum (Ferland & Netzer 1983; Halpern & Steiner 1983). Thus, the only viable polarization mechanism for the emission lines is scattering, either by dust particles or by electrons. In the following discussion, we consider the possibility that our view of the accretion disk is unobscured, and that emission lines from the disk surface are polarized by scattering within the disk atmosphere. We conclude that a more likely explanation for the narrow-line polarization is obscuration of the inner NLR by a thick torus or highly warped disk, combined with scattering above the torus midplane. In this case, our observations allow some constraints to be set on the properties of the torus and the scattering region.

#### 3.1. Scattering in the accretion disk atmosphere

We first consider the possibility that the nuclear disk is neither sufficiently warped nor sufficiently thickened at large radii to obscure a substantial part of the NLR. In this case, we would have a direct but oblique view of the surface of the accretion disk. Because of the warped shape of the disk, portions of the disk face are exposed to X-ray emission from the central engine. As discussed by Neufeld & Maloney (1995) and Herrnstein et al. (1996), the X-ray irradiation causes dissociation of molecules in the surface layers of the disk, creating a layer of warm ( $\sim 8000$  K) partially ionized gas surrounded by a fully ionized envelope. Since the X-ray flux drops off more slowly as a function of  $r$  than the disk midplane pressure, the ionization parameter actually increases with radius (Neufeld & Maloney 1995). The ionized outer regions of the disk should emit a narrow-line spectrum typical of that of Seyfert or LINER nuclei, but with an enhancement in high- $n_{crit}$  lines due to the high densities in the disk.

Radiation emerging from the surface of an accretion disk is expected to be polarized by electron scattering in the ionized atmosphere of the disk. For an electron-scattering atmosphere with infinite optical depth, the numerical results of Chandrasekhar (1960) show that the expected polarization is  $p = 11.7\%$  at  $i = 90^\circ$ , dropping to 9.0% at  $i = 87^\circ$  and 7.5% at  $i = 84^\circ$ , with the polarization angle oriented parallel to the projected surface of the disk. Since the observed emission-line polarizations are oriented parallel to the disk plane, it is worthwhile to consider whether this type of polarization due to disk emission could be occurring in NGC 4258. In this scenario, the correlation between  $p$  and  $n_{crit}$  would be ascribed to the tendency for lines of high  $n_{crit}$  to be emitted preferentially by dense gas in the disk, and polarized in the disk atmosphere, while lines of low  $n_{crit}$  would have larger, unpolarized contributions from NLR gas surrounding the disk. Because of the nearly edge-on orientation of the disk, the X-ray obscuring column could be provided by a warp in the masing disk rather than by a geometrically thick torus.

However, it is unlikely that the NGC 4258 disk could have the structure required to generate the observed high polarizations in this manner. The detailed discussion of accretion disk polarization by Chen et al. (1997) shows that two conditions are required in order to generate polarizations of up to 11.7% oriented parallel to the disk

<sup>9</sup>One other example of a Seyfert 2 galaxy having broadened forbidden lines in its polarized flux spectrum is IRAS 20210+1121 (Young et al. 1996). Young et al. propose that a portion of the NLR in this galaxy is obscured and that the narrow-line polarization is the result of scattering outside the obscuring region.

plane. The first is that the emission-line source must be located below the scattering atmosphere. An emission-line source mixed cospatially with the scattering atmosphere would generate polarization perpendicular to the disk plane, unlike what is observed in NGC 4258. Second, the Chandrasekhar results are valid for scattering optical depths exceeding  $\tau \approx 4$ . Lower optical depths would lead to polarizations much less than 11.7%, or polarizations oriented perpendicular to the disk axis. However, an electron-scattering atmosphere with a high optical depth would prevent ionizing photons from reaching a line-emitting layer located below the scattering atmosphere, and some other mechanism such as shock heating in the disk would be required to generate the emission lines. Thus, external illumination of an accretion disk would most likely lead to polarizations of  $< 10\%$ , possibly oriented perpendicular to the disk plane, unlike what is observed in NGC 4258.

Emission from a disk might be expected to produce double-peaked emission profiles, which have not been observed in NGC 4258, but electron scattering in the disk atmosphere could mask this signature by broadening the profiles. Low-velocity emission from narrow-line gas surrounding the disk at larger radii would also tend to fill in the centers of the profiles.

Even if the accretion disk were somehow able to produce Chandrasekhar-type polarization, the observed emission-line polarizations in NGC 4258 are too high to be consistent with this model because the disk is not quite edge on, and because there is some extended emission from the surrounding NLR, which we assume to be unpolarized. For [O II]  $\lambda 7325$ , the polarization of  $13.9\% \pm 1.4\%$  exceeds the theoretical maximum of 11.7% for the disk-emission model, although only by  $1.6\sigma$ . The best-fitting warped disk models of Herrnstein et al. (1996) indicate that the masing portion of the disk has  $i = 82 - 84.5^\circ$ , for which the expected polarization of disk emission is only  $6.5 - 7.5\%$ . The [O III] line polarization falls within this range, but the *HST* image shows that nearly half of the [O III] flux in the Keck aperture does not come from the unresolved central source. Thus, even under the assumption that the unresolved [O III] source is a disk with intrinsic polarization of 7%, the off-nuclear emission would dilute the observed [O III] polarization to a level of  $p \approx 3.5\%$ .

Therefore, despite the intriguing possibility that the emission-line polarizations might be generated within the accretion disk, we consider it unlikely that this scenario applies to NGC 4258. This leaves the standard obscuring torus model as the most likely polarization mechanism.

### 3.2. Scattering outside an obscuring torus

In Seyfert 2 nuclei with polarized broad-line emission, such as NGC 1068 (Antonucci & Miller 1985), the polarization is generally thought to result from scattering by dust or electrons located in the opening cone of an optically and geometrically thick torus. W95 argued in favor of this model for NGC 4258 in light of the fact that the continuum and emission lines are polarized nearly parallel to the disk plane. The high narrow-line polarizations (7.2% for [O III] and 13.9% for [O II]  $\lambda 7325$ ) imply that a substantial fraction of the NLR must be obscured from direct view. Therefore, for this model to apply to the narrow emission lines in NGC 4258, the disk must be either opaque and highly warped, or it must be surrounded by

a thick torus, at radii larger than the size of the masing region.

In the context of the obscuring torus interpretation, the observed dependence of  $p$  on  $n_{crit}$  can be interpreted as resulting from the combined effects of density stratification of the NLR gas and obscuration of the NLR by a thick torus or strongly warped disk. Lines of higher  $n_{crit}$  are preferentially emitted from denser portions of the NLR lying closer to the central source (possibly by the disk itself), and hidden from direct view by the obscuring torus, and lines of lower  $n_{crit}$  would be emitted by more diffuse gas at larger radii, and less strongly affected by the obscuring torus and scattering medium. A similar phenomenon has been proposed to explain observations of polarized [O III]  $\lambda 5007$  emission in radio galaxies (di Serego Alighieri et al. 1997).

Some constraints on the size of the obscuring torus can be derived from the compact [O III] morphology. Since the core of the [O III] emission is nearly unresolved, the angular size of the obscuring torus cannot be much larger than the size of the [O III] core in the *HST* image, or 2.5 pc. A larger torus would most likely be visible as a dark band across the nucleus. The possibility that the obscuring material is in the form of a highly warped thin disk rather than a thick torus should also be considered, but the same constraints on the size of the obscuring material would apply. As an alternative to the warped disk models, Kartje et al. (1999) have proposed that the masing clouds are lifted above the disk surface in a hydromagnetically driven wind. The dusty outer portions of a disk-driven wind could constitute the obscuring torus (e.g., Königl & Kartje 1994), and in this case the torus size would be naturally related to the size of the masing disk.

The broadening of [O III] in polarized light may be a result of interaction with the scattering medium, but to some extent it must reflect the greater velocities of clouds which are located closer to the nucleus and obscured by the torus. For electron scattering, it is possible to determine an upper limit to the scattering medium temperature from the amount of line broadening. Using the quantity  $\Delta u_{th}$  to represent the difference in quadrature between the line FWHM in polarized light and in total light, the electron temperature in the scattering medium is limited by  $T_e \leq m_e \Delta u_{th}^2 / (16k \ln 2)$  (Miller et al. 1991). From the [O III] linewidths, we find  $T_e \leq 4400$  K. As a comparison, in NGC 1068 the scattering medium is found to have an electron temperature of a few  $\times 10^5$  K (Miller et al. 1991). The unusually small degree of line broadening in NGC 4258 could be an indication that dust scattering, rather than electron scattering, is the dominant polarization mechanism.

Using FWHM/2 as an estimate of the Keplerian velocity, the [O III] linewidth of  $530 \text{ km s}^{-1}$  in total light corresponds to a typical radius of 1.6 pc, which is six times larger than the outer radius of the masing portion of the disk. If the [O III] line in polarized light is not significantly broadened by scattering, then the linewidth of  $1010 \text{ km s}^{-1}$  corresponds to a typical radius of  $r \approx 0.7$  pc, small enough to fit within a torus of diameter 2.5 pc. On the other hand, if the torus is smaller than  $\sim 1.5$  pc in diameter or if the emission lines are broadened by scattering, this would imply that the high-density portion of the NLR, from which the polarized emission originates, is larger than the size

of the torus; this would pose difficulties for the obscuring torus interpretation.

W95 estimated a size of  $\sim 35$  pc for the continuum scattering region, based on their imaging polarimetry observations. However, the compact morphology of the [O III] emission, and its relatively high polarization of 7%, suggest that the scattering region is likely to be smaller than this estimate by an order of magnitude or more. If the polarized [O III] emission originates from the compact nuclear source seen in the *HST* image, then the scattering material would have to be located within a region of diameter 2.5 pc surrounding the nucleus. W95 describe the nuclear polarization as “marginally resolved” but do not give a quantitative comparison with the seeing disk size. One possible explanation is that the apparent extension of the nuclear polarization in their image could result from atmospheric seeing combined with a foreground of interstellar polarization within NGC 4258, which is visible throughout their map. Imaging polarimetry in the continuum and the [O III] line with *HST* would provide improved constraints on the size of the scattering region. If the torus is aligned with the maser disk and oriented nearly edge-on, then the scattering material must lie above and/or below the obscuring torus, rather than within the inner “hole” (as in the model of Heisler et al. 1997).

If the scattering region is a cone (or bicone) extending above the plane of the obscuring torus, then the opening angle of the cone can be estimated from the degree of polarization of the scattered radiation. For a given torus inclination, broad scattering cones produce lower polarization than narrow cones because the light reflected from a broad region contains radiation scattered from different parts of the cone with a wider range of polarization angles. The degree of polarization of the scattered narrow-line and continuum emission in NGC 4258 is unknown; the 13.9% polarization of [O II]  $\lambda 7325$  can be taken as a lower limit to the intrinsic degree of polarization. Using as a guide the calculations presented in Figure 5 of Hines & Wills (1993), which are based on the method of Brown & McLean (1977), for  $i$  in the range  $80$ – $90^\circ$  and  $p \geq 14\%$ , the scattering cone half-angle is  $\theta_c \leq 70^\circ$ . If the off-nuclear emission-line regions seen in the *HST* image are in fact ionization cones photoionized by the AGN, the widths of these regions would imply a torus half-opening angle of roughly  $\sim 60^\circ$  (for the southern region) and  $\sim 50^\circ$  (for the northern region).

The polarized continuum flux at  $5500 \text{ \AA}$  is  $f_\lambda = 1.3 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ . Based on the results of the starlight subtraction procedure, an upper limit to the nonstellar continuum flux in total light is  $f_\lambda(5500 \text{ \AA}) < 2.1 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ . To be consistent with this upper limit, the nonstellar continuum must have  $p > 6\%$ . A reliable estimate of the intrinsic optical continuum luminosity would provide valuable constraints on accretion models and on the accretion rate in NGC 4258 (Gammie et al. 1999). Unfortunately, the unknown scattering geometry and scattering optical depth render any such estimates (such as those presented by W95) highly uncertain.

If there is a thick obscuring torus in NGC 4258, then some fraction of the UV/X-ray continuum will be intercepted by the torus and reprocessed to infrared (IR) wavelengths. The far-IR flux of the NGC 4258 nucleus has

been measured only at  $10 \text{ \mu m}$  (Rieke & Lebofsky 1978), and part of the observed far-IR emission must be primary radiation from the accretion flow itself (e.g., Gammie et al. 1999), so it is difficult to place meaningful constraints on the reprocessed IR luminosity. NGC 1068 is a factor of  $\sim 200$  brighter than NGC 4258 both in observed [O III] flux and at  $10 \text{ \mu m}$  (using measurements from Ho et al. 1997b, Shields & Oke 1975, and Rieke & Lebofsky 1978). However, in NGC 1068 the [O III] emission is considered to be unobscured (Miller et al. 1991) while in NGC 4258 the [O III]-emitting region must be substantially hidden by the torus. We caution against drawing any conclusions based on such a simple comparison, as the properties of the torus in NGC 4258 are poorly constrained at best and the existing observations do not allow us to distinguish between the possible models for the observed IR emission.

W95 found that the polarized continuum shape over  $4580$ – $7110 \text{ \AA}$  was adequately fit by a  $f_\nu \propto \nu^{-1.1}$  power law. In our spectra, however, the Stokes flux continuum drops off shortward of  $5000 \text{ \AA}$ , even after correcting for the amount of polarized flux lost due to the slit misalignment. If this turnover is a genuine feature of the nonstellar continuum, its shape can be used to constrain the accretion rate (for thin-disk models), or the transition radius between a thin accretion disk and an advection-dominated accretion flow (Gammie et al. 1999). Further observations at shorter wavelengths are needed to determine whether this turnover is indeed a feature of the nonstellar continuum, or whether it may instead be an artifact resulting from interstellar polarization within NGC 4258 or the Galaxy. The total contribution of interstellar polarization (including interstellar polarization within NGC 4258) could be determined, in data of higher signal-to-noise ratio, by measuring the equivalent widths of stellar absorption features such as Ca II H+K or the Mg  $b$  lines in the Stokes flux spectrum.

#### 4. CONCLUSIONS

The narrow-line properties of NGC 4258 are unusual in comparison with those of most Seyfert 2 nuclei in which hidden broad-line regions have been detected. Its narrow forbidden lines are highly polarized, with  $p$  as high as 13.9%, and the degree of polarization is correlated with the critical density of the transitions. The [O III]-emitting region is compact and centered at the nucleus, with a nearly unresolved core of FWHM  $\lesssim 2.5$  pc.

Determining the mechanism responsible for the narrow-line polarization in NGC 4258 is of relevance to AGN unification models in general, as it pertains to the question of whether or not *all* Seyfert nuclei contain a geometrically thick obscuring torus. Despite the superficial resemblance between the observed narrow-line polarizations and the predicted polarization for an edge-on emission source with an electron-scattering atmosphere (Chandrasekhar 1960), the disk-emission model probably does not apply to this object; the requirement of high scattering optical depth is probably unrealistic, and the line polarizations are too high. Scattering above the plane of an obscuring torus, or above a highly warped thin disk, is the most likely explanation for the narrow-line polarizations in NGC 4258, as first proposed by W95. From the compactness of the [O III] emission, we estimate that the torus must have a diameter of  $\lesssim 2.5$  pc.

The geometry of the obscuring material relative to the masing disk remains an open question. The masing disk may simply be so warped in its outer regions that it hides the inner portion of the NLR from our direct view. If the disk is more nearly flat, then the masing region could be located at the midplane of the obscuring torus where the geometry is favorable for maser amplification, or the torus might surround the masing disk at larger radii. Alternatively, if the masing clouds are located in a wind driven from the disk surface, as in the model of Kartje et al. (1999), then the wind itself would provide the obscuring material.

There is no direct evidence in our data for a broad component of  $H\alpha$  in total or polarized light, but we cannot exclude the possibility that a broad component may be present. If the continuum source and part of the NLR are hidden by an opaque torus, and if NGC 4258 does contain a BLR, then the BLR should be entirely obscured and the broad-line emission detected in higher-resolution spectra should consist entirely of scattered light. A clear detection of a polarized broad component of  $H\alpha$  would provide

strong support for the obscuring torus interpretation.

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## Figure Captions

FIG. 1.— Polarization data for NGC 4258. (a) Total flux, in units of  $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ . (b) Degree of linear polarization, given as the rotated Stokes parameter. (c) Stokes flux, equal to the product of (a) and (b), in units of  $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ . For clarity, the spectra have been binned to  $4 \text{ \AA pix}^{-1}$ .

FIG. 2.— Comparison of emission-line profiles in total flux and Stokes flux. *Solid line*: Total flux spectrum after removal of starlight, in units of  $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ . *Dotted line*: Continuum-subtracted Stokes flux, scaled by a factor of 16 to achieve a rough match with the emission-line strengths in total flux for comparison purposes.

FIG. 3.— Forbidden-line polarization as a function of  $n_{crit}$  and ionization potential. The open circle represents the polarization of [N II] measured from the 4-Gaussian fit including a broad  $H\alpha$  component, while the triangle represents the [N II] polarization derived from the 3-Gaussian fit without a broad  $H\alpha$  component.

FIG. 4.— *Left panel*— Continuum-subtracted *HST* WFPC2/PC F502N image of NGC 4258 showing emission from [O III]  $\lambda 5007$ . *Right panel*— F547M (V-band) PC image of NGC 4258. The image section is  $20'' \times 20''$ , and the rectangle surrounding the nucleus shows the region included in the  $1'' \times 3''/4$  spectroscopic extraction. The masing portion of the disk has a diameter of  $\sim 0''.015$  (Miyoshi et al. 1995), or about one-third the size of a PC pixel. At  $D = 7.3 \text{ Mpc}$ ,  $1''$  corresponds to 35 pc.



TABLE 1  
LINE AND CONTINUUM PROPERTIES

Line	$n_{crit}^a$ ( $\text{cm}^{-3}$ )	IP (eV)	$f/f(\text{H}\beta)^b$	FWHM(tot) <sup>c</sup> ( $\text{km s}^{-1}$ )	FWHM(pol) <sup>d</sup> ( $\text{km s}^{-1}$ )	$p$ (%)	$\theta$ ( $^\circ$ )
H $\beta$ .....	...	...	1.0	$690 \pm 90$	$1200 \pm 400$	$6.3 \pm 1.0$	$95 \pm 4$
[O III] $\lambda 4959$ .....	$6.2 \times 10^5$	54.9	1.2	$520 \pm 60$	$1240 \pm 220$	$6.9 \pm 0.7$	$89 \pm 3$
[O III] $\lambda 5007$ .....	$6.2 \times 10^5$	54.9	3.3	$530 \pm 30$	$1010 \pm 70$	$7.2 \pm 0.3$	$89 \pm 1$
[O I] $\lambda 6300$ .....	$1.6 \times 10^6$	13.6	1.0	$500 \pm 30$	$780 \pm 180$	$5.0 \pm 1.1$	$91 \pm 7$
[O I] $\lambda 6363$ .....	$1.6 \times 10^6$	13.6	0.3	$300 \pm 110$	...	$5.9 \pm 2.4$	$76 \pm 11$
H $\alpha$ + [N II] blend.....	...	...	6.7	...	...	$7.9 \pm 0.2$	$89 \pm 1$
H $\alpha^e$ .....	...	...	3.8	$660 \pm 30$	$1170 \pm 220$	$8.0 \pm 0.7$	$89 \pm 1$
[N II] $\lambda 6583^e$ .....	$8.0 \times 10^4$	29.6	2.0	$330 \pm 20$	$1120 \pm 250$	$7.7 \pm 1.0$	$90 \pm 2$
[S II] $\lambda 6716$ .....	$1.6 \times 10^3$	23.3	0.8	$310 \pm 20$	...	$1.0 \pm 0.6$	$90 \pm 9$
[S II] $\lambda 6731$ .....	$1.5 \times 10^4$	23.3	0.9	$310 \pm 20$	...	$3.1 \pm 0.6$	$90 \pm 2$
[Ar III] $\lambda 7136$ .....	$4.9 \times 10^6$	40.7	0.2	$600 \pm 120$	...	$7.0 \pm 3.4$	$87 \pm 14$
[O II] $\lambda 7325^f$ .....	$5.7 \times 10^6$	35.1	0.8	$870 \pm 50$	$1350 \pm 150$	$13.9 \pm 1.4$	$89 \pm 3$
Continuum 4000–4800 Å						$0.38 \pm 0.03$	$74 \pm 2$
Continuum 5100–6100 Å						$0.35 \pm 0.01$	$79 \pm 1$
Continuum 7500–8500 Å						$0.29 \pm 0.02$	$78 \pm 2$

<sup>a</sup>Critical densities calculated for  $T = 10^4$  K using the IRAF/STSDAS task nebular.ionic.

<sup>b</sup>Total flux of line relative to  $f(\text{H}\beta) = 1.7 \times 10^{-14}$  erg cm $^{-2}$  s $^{-1}$ , not corrected for reddening; this H $\beta$  flux may include a contribution from the broad-line component.

<sup>c</sup>Full width at half-maximum of line in total flux, corrected for instrumental broadening.

<sup>d</sup>Full width at half-maximum of line in Stokes flux, corrected for instrumental broadening.

<sup>e</sup>For the H $\alpha$ + [N II] blend, the component polarizations listed here are the values derived from the 3-Gaussian fit which does not include a broad H $\alpha$  component.

<sup>f</sup>[O II]  $\lambda 7325$  refers to the unresolved  $\lambda\lambda 7319, 7331$  blend, which may contain some [Ca II]  $\lambda 7324$  emission as well.







